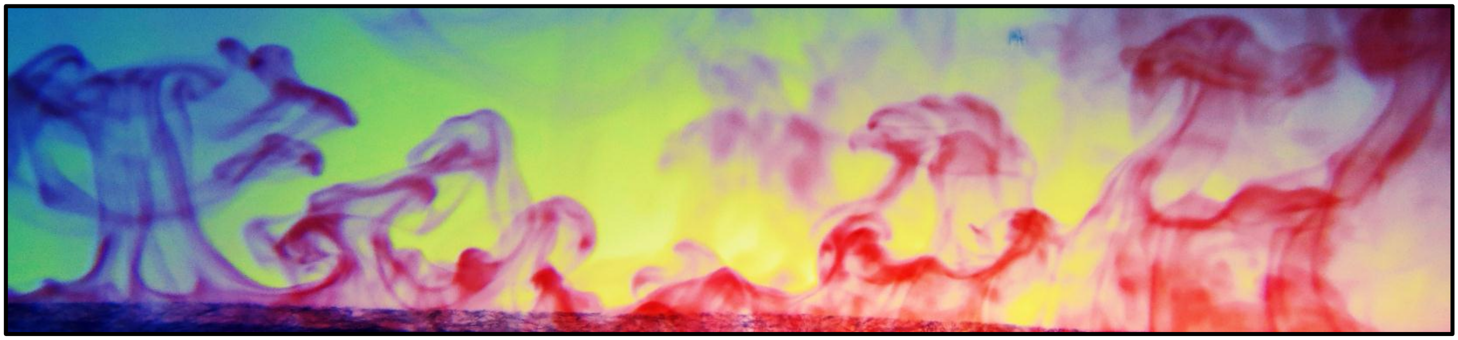
Stalking the Predator



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Flow Visualization

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Purpose

While enjoying a cup of hot tea I was once again entranced by the beauty of the dyed colorful streams of tea particles falling elegantly from the bottom of the bag of tea. I wanted to capture beauty in the chaotic streams of tea as they initially rush into their new environment and eventually slow their progress as they turn the water into tea. I wanted to share this beauty through photography as well as investigate why the tea particles behave the way they do. I titled the image 'Stalking the Predator' because the tea particles form the shape of the head of a snake a third from the left side of the image and the head of an eagle stalking behind it a third from the right side of the image. In a University of Colorado course called Flow Visualization I created this experiment to capture the falling tea particles for our first ('Get Wet') assignment where we are encouraged to have fun playing with whatever fluid phenomenon we want to explore and get our feet wet in the fields of photography and flow visualization. I am an undergraduate student at the University of Colorado studying Mechanical Engineering. I have no prior experience in photography, but I do have some experience dealing with basic fluid mechanics. My colleague, Zach Brunson, helped me prepare the apparatus used to produce the flow of the tea particles which is a tea bag suspended in a flat glass container by a string hanging from a rod on the top of the glass container.

Experimental Set Up

The apparatus that I used to produce the flow can be seen in Figure 1. I heated the water

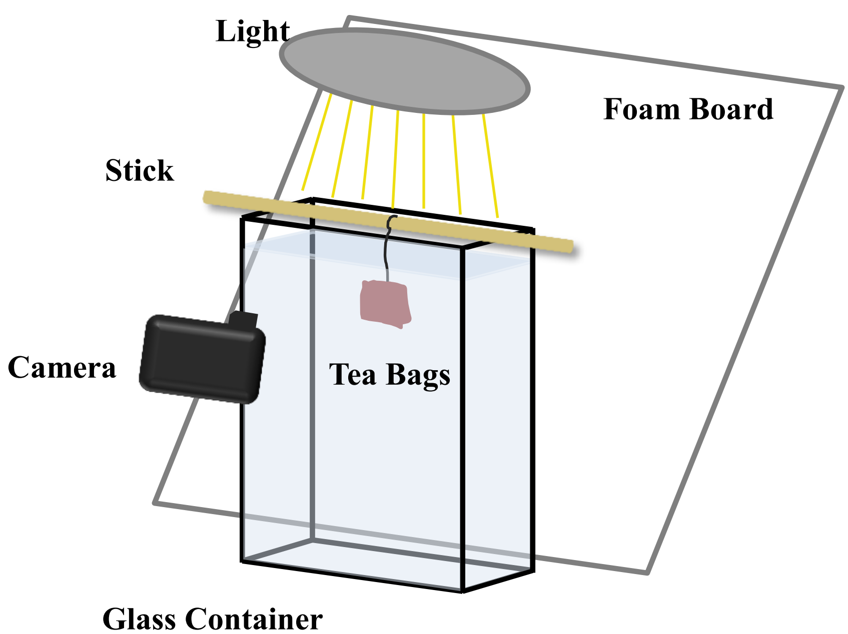

Figure 1: Sketch of Apparatus

in a pot until it was boiling, and then I transferred the boiling water from the pot into the glass container seen in Figure 1 until it was full within two centimeters of the top. I then placed two tea bags that were tied together and suspended from a rod with a string. I placed a light directly over the water container. In order to provide a clean image without a distracting background and with the best light possible I placed a matte white foam board directly behind the glass container, and I angled it at approximately a 60^0 to distribute the light evenly across the apparatus. This eliminated the possibility of having a glare reflecting off of the glass container. The foam board is 77x52cm, the glass container is 6x19x28cm, and the tea bag is 6x7cm. The tea bag saturates the water inside of it with tea particles increasing the saturated water's density to greater than the density of normal water. The denser particle filled water falls down through the unsaturated clear water because of the gravity force that is acting on it and the inability of the less dense clear water to hold up the denser particle filled water as described in the Rayleigh-Taylor Instability (RTI).[1-3]

Physics of the Flow

I have provided a very general explanation for the reason that tea saturated water falls through the unsaturated water, but how does the RTI actually work? The RTI describes how two fluids of different densities will behave when the denser fluid is above the lighter fluid with respect to gravity. The lighter fluid is supporting the heavier fluid until there as a small disturbance in the previously flat interface between the fluids. This disturbance causes the lower point in the fluid to need more pressure to hold it up and the higher point needs less pressure to hold it up. The instability then takes affect because there is not enough pressure to hold up the lower portion, and the denser fluid begins to propagate down in the shape of fingers.[1-3] These fingers increase downward exponentially as the lighter fluid cannot hold up the heavier fluid once the unstable surface has been disturbed. This does not need to be large or visible; the interface is so delicate that RTI takes over almost immediately and uncontrollably.[1-3] With my experiment the water saturated with tea particles is denser than the unsaturated water that it is above with relation to the gravity force acting on it, and it therefore falls down through the lighter water exhibiting the RTI. I found the density of water to be (ρ_L) 965.3 kg/m^3at a water temperature of 90⁰C, which is the approximate temperature that the water was at, described by Newton's law of cooling seen in Equation 1.[4-6]

$$T(t) = T_A + (T_H - T_A)e^{-kt} = 21 + (100 - 21)e^{-4.2*[2/60]} \approx 90°\text{C}$$

Equation 1

I found the density if the tea to be (ρ_H) 1216 kg/m^3 by taking a sample of the tea and measuring its volume and weight to obtain its density. I then compared the density of the tea to the density of the water, and as you can see the tea is denser than the water. In the RTI this density ratio is called the Atwood number and it is calculated by Equation 2.

$$A = \frac{\rho_H - \rho_L}{\rho_H + \rho_L} = \frac{1216 - 965.3}{1216 + 965.3} = 0.1149$$

Equation 2

The Atwood number describes what the flow will look like, "If A≤1, the light fluid moves into the heavy fluid in the form of round topped bubbles with circular cross sections."[1] This can be viewed in the image by looking at the negative space: the lighter unsaturated water. As the fingers move down and speed up through the flow there is shear created between the interface of the falling saturated tea and the still unsaturated water. This drag causes the vortices, bubbles, and mushrooms and they are described by the Helmholtz Instability.[1] This instability can be seen all across the image as the saturated tea water curls back created mushrooms and vortices because of the drag-shear force created between the interfaces of the moving and still fluids.[1] The approximate Reynolds number of the falling tea when this image was taken is calculated by Equation 3.[8]

$$Re = \frac{Dv}{\mu} = \frac{.0015 * .01}{3.6 * 10^{-10}} = 4205$$

Equation 3

I took the approximate diameter of the fingers being formed by the tea for D, the approximate velocity for tea falling[7], and the average density of water and tea along with the viscosity of water for μ at the specified temperature. I assumed the viscosities to be very similar.

Visualization Technique

I used tea particles from tea bags to turn the water red and make it denser than its surrounding water. The tea type I used was the Wild Berry Zinger Tea by Celestial Seasonings because of its deep vibrant red color. The water was boiled in a pot on the stove and then it was allowed to sit in room temperature air in the glass container and cool for approximately two minutes before the tea bag was placed in the water. From Newton's Law of Cooling I calculated the temperature of water after two minutes as seen in Equation 1. The tea bags were completely dry and at room temperature when I placed them in the water. I obtained the glass container, rod, string, and foam board from Michael's hobby store. I purchased the tea from Safeway grocery store. I used a desk lamp that I already had at home for several years as my lighting source. This lighting source is a compact fluorescent (CFL) four tube Lights of America FML-27EX-D (120V, 60Hz, 27W) light bulb. I chose to use a CFL over an incandescent light bulb because it provided more contrast between the red tea particles and the white background. I placed the light centered directly over the glass container approximately fifteen centimeters above the top of the container. The only other light in the room was in direct sunlight coming through the windows in the room, and this did not have a noticeable effect on the image. I did not use a flash on the camera because I did not want to produce a glare spot on the glass I was shooting through.

Photography and Post Processing

I chose to shoot a very small portion of the flow in order to get the most detail possible while eliminating the possibility of distraction by having too much going on in the image at too far of a distance to study anything specific or obtain a beautiful pattern. For this reason I originally shot a field of view that is approximately 4cm in width and 3cm in height as seen in Figure A-1 in the Appendix. The original image is 4000 pixels in width and 3000 pixels in height. I further cropped the image using Photoshop from there to approximately 3.1cm in the width and 0.6cm in height to eliminate the distracting parts of the image and keep only the most beautiful and interesting part of the flow. The cropping I did produced an image that is 3526 pixels in width and 792 pixels in height. After cropping I turned the image upside down because I liked the aesthetic appeal of the appearance of a rising fluid over a falling fluid in this instance. From there I used the curves tool in Photoshop to bring out the contrast between the off-white color of the partially dyed tea-water and the more heavily saturated tea-water that were producing the observed flow characteristics. I did this by using an 'S' curve in the RGB spectrum which I learned from Professor Hertzberg in my Flow Visualization class. At this point the image had more contrast, but it still did not have the colors I desired or the vast contrast difference I desired. After some verbal help from my colleague Zach Brunson, I proceeded to manipulate the red, green, and blue colors in the image independently with the curves tool until I obtained the beautiful, colorful, and contrasted image that I desired which can be observed on the cover of this document. The work that I performed with the curves function can be seen in the Appendix. The distance from the tea bag to my lens is approximately 10 cm. I used Cannon Powershot SX 260 HS which is a digital film camera with 12.1 megapixels. To produce this image I set the camera to a low ISO setting of 100 in order to produce a clean image with the least amount of noise possible. I then chose my lowest F-stop of f/3.5 because I did not need a great depth of field and I wanted to produce the sharpest image possible. After that I slowed down my shutter speed enough to get the color contrast that I wanted without getting motion blur. This shutter speed value was 1/20 second. I then used a focal length of 4.5mm to produce the most in focus image.

Conclusion

My image reveals the beauty in the chaos of the everyday phenomenon of tea falling from a tea bag into a cup of tea. After the post processing adjustments that I made to the photograph I achieved exactly what I wanted to show which was both clearly defined flow physics and a an aesthetically pleasing image. I did not like the washed out appearance that the original image gave, but after the post processing the colors that I was able to bring out became one of my favorite parts. In the future I would like to be able to image several different colors of tea falling side by side. In order to do this I would need to image their side view and line them up very close together instead of their front. This would allow me to produce a colorful image with less post processing staying more true to the actual colors of the image. Overall I was very satisfied with the flow that I was able to capture in the original image and the beauty that I was able to bring out through post processing the image.

Appendix

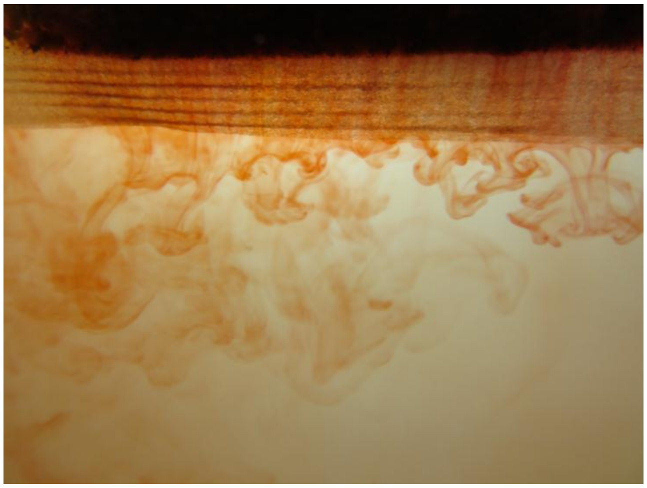

Figure A-1: Original Image

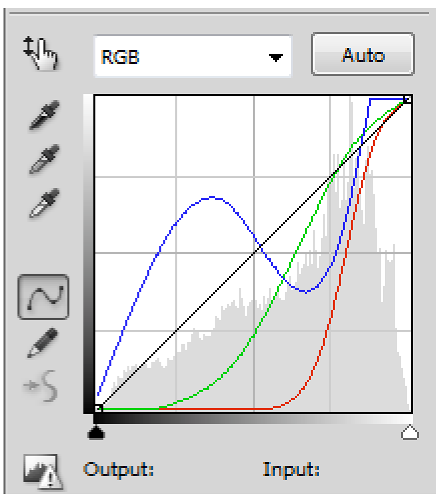

Figure A-2: Photoshop Curves Tool

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[4] "Water - Density and Specific Weight." *Water - Density and Specific Weight*. N.p., n.d. Web. 14 Feb. 2013. <http://en.wikipedia.org/wiki/Properties_of_water>.

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[8] "Reynolds Number." *Reynolds Number*. N.p., n.d. Web. 14 Feb. 2013. <http://www.engineeringtoolbox.com/reynolds-number-d_237.html>.